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A Systematic Review of Reliability and Safety in Nuclear Power Plants

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The safe operation of nuclear power plants is a cornerstone of energy security and socioeconomic development, with the reliability of Pressurized Water Reactors (PWR) depending on the effectiveness of inspection and maintenance plans for their critical components. Optimization through Risk-Based Inspection (RBI) has emerged as a key methodology to balance system safety, plant availability, and economic efficiency, by focusing maintenance efforts on the most critical items. The nuclear energy industry has shown growing interest in adopting risk-based approaches to maintenance activities. In this context, this study conducts a Systematic Literature Review (SLR) to map the state of the art in optimizing inspection plans for PWR reactors, with an emphasis on RBI-oriented methods, tools, and perspectives. The review covered scientific publications from the past five years, including articles, technical reports, and international standards. The results reveal a predominance of probabilistic models integrated with tools such as Failure Mode, Effects, and Criticality Analysis (FMECA), Fault Tree Analysis (FTA), and Event Tree Analysis (ETA). Two main research axes were identified: (1) the use of computational simulation and machine learning for maintenance optimization, and (2) the application of RBI or Risk-Informed In-Service Inspection (RI-ISI), a nuclear industry–specific approach based on principles consistent with RBI. Despite recent advances, the direct application of Probabilistic Risk Assessment (PRA) for the full optimization of inspection plans remains underexplored, highlighting an important research gap for PWR reactors. It is concluded that this is an expanding field with great potential in integrating reliability methods and computational innovations. This work provides an up-to-date overview, serving as a guide for future research and the development of more robust and safer inspection practices.

Keywords: Pressurized Water Reactor (PWR); Inspection Plan Optimization; Risk-Based Inspection (RBI); Reliability Analysis; Probabilistic Risk Assessment (PRA); Nuclear Safety.

1. Introduction

Safety and operational reliability are fundamental principles of the nuclear industry, as failures in critical systems may lead to severe consequences for society, the environment, and the long-term sustainability of the sector. Nuclear power plants are therefore designed according to the defense-in-depth concept, relying on redundancy, diversity, and rigorous inspection and maintenance programs to reduce failure probability and mitigate consequences. Component and system reliability is essential to ensure regulatory compliance, safe operation, and public acceptance of nuclear energy (Kiani & Steen, 2022).

Pressurized Water Reactors (PWRs) are the most widely deployed nuclear technology worldwide, largely due to their technological maturity, standardized design, and extensive operational experience. In the context of the energy transition, PWRs play a strategic role by providing reliable baseload electricity with low life-cycle carbon emissions. Their safe and continuous operation depends on the integrity of critical systems and components, whose degradation can adversely affect both safety and availability (Mohammadhasani & Pirouzmand, 2021).

Inspection and maintenance planning is a key element in ensuring component integrity and preventing unplanned outages. However, traditional time-based approaches often lead to inefficient resource allocation. As a result, risk-based methodologies, such as Risk-Based Inspection (RBI) and Risk-Informed In-Service Inspection (RI-ISI), have gained prominence by prioritizing components according to failure probability and consequence, improving both efficiency and safety (Shafiee & Guedes Soares, 2020; Bhatia et al., 2019; Wang et al., 2025).

Given recent advances in computational tools, probabilistic methods, and data-driven techniques, a systematic literature review is warranted to consolidate current knowledge on risk-based reliability and inspection optimization in nuclear power plants. The literature reveals a fragmented treatment of reliability, safety, and inspection, underscoring the need for integrated approaches. In particular, although Probabilistic Risk Assessment (PRA) is well established in nuclear safety analysis, its comprehensive application to the optimization of inspection plans for PWRs remains limited and insufficiently explored (Kiani & Steen, 2022).

1.1. Objective of the study

In light of this context, the objective of this study is to map and analyze, through a Systematic Literature Review of the past five years, the state of the art of reliability and safety approaches in nuclear power plants, with a focus on the optimization of inspection plans. The study emphasizes methodologies based on Risk-Based Inspection (RBI), aiming to identify methods, tools, research trends, and gaps, particularly with regard to the application of Probabilistic Risk Assessment (PRA) in Pressurized Water Reactor (PWR) systems.

2. Theoretical basis

Reliability engineering plays a central role by providing quantitative methods to evaluate the performance of structures, systems, and components and their contribution to global risk metrics, such as Core Damage Frequency (CDF) (Nilsson, 2003).

Probabilistic Risk Assessment (PRA) constitutes the primary tool for establishing this connection, as it enables a structured representation of the relationship between component failures, accident sequences, and associated consequences. From a formal standpoint, CDF can be expressed as the sum of the individual contributions of components, resulting from the combination of their failure frequencies and consequence factors that depend on system topology. This decomposition highlights that overall plant safety depends not only on system robustness but also on the individual reliability of components and their functional interactions (Nilsson, 2003).

In Pressurized Water Reactors (PWRs), which are characterized by high pressures, high temperatures, and long operating cycles, the reliability of structures, systems, and components (SSCs) is particularly critical. Degradation mechanisms such as intergranular stress corrosion cracking, thermal fatigue, and high-frequency vibrations primarily affect passive components, such as piping systems, whose failure may act as initiating events for Loss-of-Coolant Accidents (LOCAs). Applied studies demonstrate that the combination of operational stresses, residual stresses, and degradation mechanisms dominates the contribution of these components to CDF, reinforcing the need for probabilistic fracture and lifetime models to support inspection and maintenance decision-making (Brickstad et al., 2002).

In addition to failures themselves, component unavailability constitutes a key element in the integrated assessment of nuclear reliability and safety. In PRA, unavailability is defined as the fraction of time during which a component or system is not capable of fulfilling its safety function, whether due to random failures, corrective maintenance, inspections, periodic testing, or scheduled repairs. Unavailability therefore incorporates both technical and organizational parameters, such as mean repair times, maintenance strategies, and operational planning, directly influencing risk metrics (Nilsson, 2003).

From this perspective, prolonged periods of unavailability can significantly increase the probability of accident sequences, even when intrinsic component failure rates are low. In redundant systems typical of PWRs, the simultaneous unavailability of safety trains resulting from poorly coordinated inspection or maintenance activities can temporarily undermine defense-in-depth principles.

Traditional inspection and maintenance approaches, based on prescriptive criteria and fixed intervals, although conservative, tend to address this interaction between degradation, failure, and unavailability in a limited manner. In this context, Risk-Based Inspection (RBI) and Risk-Informed In-Service Inspection (RI-ISI) methodologies have emerged as alternatives capable of prioritizing inspections by explicitly considering the contribution of each component to overall plant risk. Studies show that such approaches make it possible to reduce the total number of inspections and occupational radiation exposure while maintaining (or even reducing) CDF by concentrating efforts on components of greater safety significance (Brickstad et al., 2002).

In the context of optimizing risk-informed inspection and maintenance plans, metaheuristic algorithms have been increasingly explored, expanding the scope for applications based on artificial intelligence (AI). Algorithms such as the Cuckoo Search Algorithm, for example, have been successfully applied to inspection planning and maintenance activities, enabling efficient searches for optimal or near-optimal solutions in high-dimensional decision spaces, where conventional deterministic approaches prove limited (Alegrio & Nicolau, 2025). The population-based search mechanism and the ability to avoid local optima make this algorithm particularly suitable for complex optimization problems in nuclear maintenance.

From a regulatory perspective, this conceptual evolution is recognized by both the International Atomic Energy Agency (IAEA) and the U.S. Nuclear Regulatory Commission (NRC). The IAEA states in its safety standards that regulatory and operational decisions may be supported by risk-informed approaches, provided that they are used as a complement to (and not a replacement for) deterministic analyses and defense-in-depth principles (IAEA, 2016). Consistently, the NRC adopts the concept of risk-informed, performance-based regulation, in which PRA results are used to support decisions related to inspection, maintenance, and changes to regulatory programs while preserving adequate safety margins (NRC, 2017).

NRC regulatory documents, such as the Reactor Oversight Process and guidance related to RI-ISI, emphasize that the unavailability of components and systems should be explicitly considered in risk assessments, since degraded operational states may have a significant impact on metrics such as CDF and Large Early Release Frequency (LERF). Similarly, IAEA guidelines recommend that inspection programs consider the relative safety importance of components, relying on PRA results to optimize inspection scope, frequency, and methods (IAEA, 2016).

Accordingly, the technical literature and the regulatory framework converge in indicating that the integration of reliability, component unavailability, and probabilistic analyses constitutes the conceptual foundation for optimizing inspection plans in PWR reactors. The combination of PRA, probabilistic degradation models, advanced computational tools, and RBI and RI-ISI methodologies enables alignment between nuclear safety, operational reliability, and economic efficiency, in accordance with international regulatory expectations and the conservative principles of nuclear engineering (Nilsson, 2003; Brickstad et al., 2002; Hryshchenko et al., 2013; IAEA, 2016; NRC, 2017).

2.1. *Systematic Literature Review (SLR)*

This study adopts a Systematic Literature Review (SLR) in order to ensure transparency, reproducibility, and methodological rigor, following the framework proposed by Tranfield et al. (2003). This framework is organized into three phases, encompassing activities from the definition of the scope and inclusion and exclusion criteria to the synthesis and dissemination of results (Table 1).

Table 1: Stages of a Systematic Literature Review (SLR)

Review Steps (Tranfield, 2003)	
Stage I - Planning the revision:	It includes Phase 0, which involves identifying the need for revision; Phase I, which involves preparing the proposal, defining the scope, inclusion and exclusion criteria, databases, and search strings; and Phase II, which involves developing the revision protocol, describing the process steps and conceptually discussing the relevance of the research problem.
Stage II - Conducting the review:	It encompasses Phase III, which involves identifying studies in databases; Phase IV, which involves selecting studies according to pre-established criteria, recording exclusions and their reasons; Phase V, which involves evaluating the methodological quality and relevance of the studies; Phase VI, which involves data extraction and monitoring of progress; and Phase VII, which involves synthesizing the extracted data.

(Table 1 continues on the next page)

Stage III - Report preparation and dissemination of results:	It comprises Phase VIII, dedicated to writing the final report, including results, discussions, and recommendations, which can be initiated after defining a broad framework (Rowley and Slack, 2004); and Phase IX, focused on presenting the evidence in practice, with the public dissemination of the results of the systematic review.

To support the execution of the SLR, the online software Parsif.al was used (Parsifal, 2026; Souza, 2015). This free tool, developed in Brazil, is aligned with the planning, conduct, and reporting stages of systematic literature reviews, as proposed by Tranfield et al. (2003) and Kitchenham (2007). The tool was selected due to its methodological adherence and its ability to facilitate the organization, monitoring, and documentation of the review process. The SLR protocol was structured and managed within the platform, which provides specific support for systematic reviews in the fields of engineering and safety sciences.

3. Methodological application

This section describes the methodological application of the study, as well as the results of this application, which are discussed in Section

3.1. *Research method (steps)*

After identifying the need for the systematic literature review (Stage I – Phase 0), the study advanced to Phases 1, 2, and 3, corresponding to the preparation of the review proposal and the development of the review protocol. The search strategy was designed to capture recent advances in reliability, safety, and risk-based inspection applied to PWR-type nuclear power plants, encompassing peer-reviewed journals, conference proceedings, and selected technical reports. The search strings combined terms related to PWRs, reliability analysis, Risk-Based Inspection (RBI) and Risk-Informed In-Service Inspection (RI-ISI), probabilistic risk assessment, maintenance optimization, and machine learning, with a temporal scope limited to the past five years.

The screening of studies was conducted in multiple stages, including title and abstract analysis, full-text evaluation, and final eligibility confirmation. The selected studies were classified according to methodological approach, tools employed, application domain, and contribution to the optimization of inspection plans. Table 2 presents the classification framework used in the review proposal preparation phase, which was adopted to organize, select, and extract information based on the scope and quality of the studies.

Table 2. Preparation of the Proposed Revision

Scope:	This systematic review of the literature aims to map and analyze the state of the art of reliability and safety approaches applied to nuclear power plants, with an emphasis on pressurized water reactors (PWRs), in the period between 2021 and 2026, using the ISI Web Of Science (WOS) and SCOPUS databases. The study focuses on planning and optimization methodologies for inspection plans, considering risk-based approaches, highlighting Risk-Based Inspection (RBI) and its integration with Probabilistic Risk Assessment (PRA) techniques. Included are works that address: RBI models, frameworks, and methodologies applied to systems, structures, and components (SSCs) of nuclear power plants; / Applications of PRA/PSA as a decision support tool in inspection, maintenance, and structural integrity; / Strategies for optimizing inspection and maintenance plans, including deterministic, probabilistic, and computational methods; / Studies focused on reliability, nuclear safety, and structural integrity, provided they relate to the context of risk-based inspection; / Tools, techniques, and algorithms used for prioritization, planning, or optimization of inspections in nuclear environments; / Research trends, technical challenges, and scientific gaps related to the joint application of RBI and PRA in PWR reactors.
Search string (main):	(("pressurized water reactor" OR "PWR" OR "Nuclear Power Plant*") AND ("inspection plan*" OR "inspection plan optimization" OR "Optimization" OR "risk-based inspection" OR "RBI" OR "maintenance" OR "maintenance planning") AND ("reliability" OR "probabilistic risk assessment" OR "PRA" OR "nuclear safety"))

(Table 2 continues on the next page)

Inclusion and Exclusion criteria:	**Inclusion:** Studies within scope and with a score higher than 3.5 in the quality assessment. **Exclusion:** Duplicate studies; out-of-scope studies; studies prior to 2021 (last five years) *; closed-access studies*; studies that are not articles, conference papers, or review articles. *; Maintenance or reliability studies outside the nuclear sector; Studies focused exclusively on other types of reactors (e.g., BWR, PHWR, AGR, SMRs), when there is no applicability or relevant discussion for PWR.
Quality Assessment:	Is the study published in a journal with a high impact factor? / Is the study well-cited? (Answer "YES" for more than 10 citations - "PARTIALLY" for fewer than 10 and different from 0 - "NO" if it is 0) / Does the study's rationale contribute to the basis of this research? / Was the study's methodology well used and explained? (opinion) / Was the study appropriate to the scope of this review? / Did the study present any tools or methods applicable to the scope of this review? / Are the results of this study relevant to this review? (**Scoring for the answers: Yes (1.0 point); Partially (0.5 point); No (0 point))**

**Initial exclusion criteria: criteria that can still be applied during the search performed in the databases.*

The review protocol was modeled using BPMN (Business Process Model and Notation), illustrating the overall workflow adopted in the systematic review process and highlighting the interaction among the search, screening, and analysis stages (Figure 1). This modeling consisted of defining logical steps based on the stages proposed by Tranfield et al. (2003).

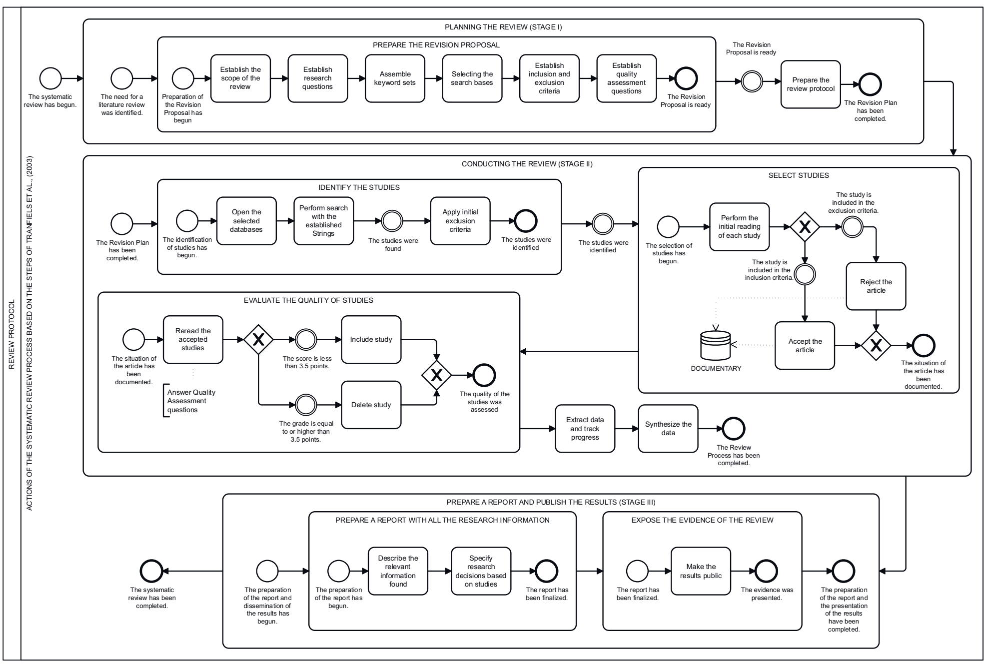

Fig. 1. Flowchart of the Systematic Literature Review Process applied in this study.

During the conduct of the review (Stage II), Phases 3 through 7 were carried out, corresponding to the identification, selection, and quality assessment of studies, as well as data extraction, tracking, and synthesis of results. In the database search stage, the following initial exclusion criteria were applied: studies published prior to 2021, studies with restricted access, and publications that did not qualify as journal articles, conference papers, or review articles. The remaining criteria were applied during the screening and eligibility phases in order to avoid the premature exclusion of potentially relevant studies.

The search strings were adapted to the specific characteristics of each database, according to the available advanced search features, and are presented in Table 3.

Table 3. Search strings for searching databases

WOS	(("pressurized water reactor*" OR "PWR" OR "nuclear power plant*" OR "nuclear power station*") AND ("inspection plan*" OR "risk-based inspection" OR "RBI" OR "inspection optimization" OR "maintenance planning" OR maintenance) AND ("reliability" OR "probabilistic risk assessment" OR "PRA" OR "nuclear safety")) (Topic) and 2026 or 2025 or 2024 or 2022 or 2023 or 2021 (Publication Years) and Open Access
Scopus	TITLE-ABS-KEY (("pressurized water reactor" OR "PWR" OR "Nuclear Power Plant*") AND ("inspection plan*" OR "inspection plan optimization" OR "Optimization" OR "risk-based inspection" OR "RBI" OR "maintenance" OR "maintenance planning") AND ("reliability" OR "probabilistic risk assessment" OR "PRA" OR "nuclear safety")) AND PUBYEAR > 2020 AND PUBYEAR < 2027 AND (LIMIT-TO (OA , "all")) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp") OR LIMIT-TO (DOCTYPE , "re"))

The number of studies retrieved per database was 122 from Scopus and 57 from the ISI Web of Science, totaling 179 articles. Of these 179 records, 48 duplicates were removed, resulting in 131 identified studies. With the identification of these studies, the subsequent phase, referred to as “Study Selection,” was initiated. The quality assessment of the studies was performed based on the scores assigned to the evaluation questions defined during the Review Planning stage. Studies that received a score lower than 3.5 were considered rejected. Finally, data extraction was conducted.

Based on the reading of the study abstracts and considering all the established inclusion and exclusion criteria, all 131 studies were deemed relevant.

3.2. *Main results of the methodological application*

The analyzed literature indicates a predominance of probabilistic and risk-informed approaches in the context of nuclear reliability and safety, often combined with classical reliability models and system-level risk analyses (Mandelli et al., 2023; Cancemi et al., 2023; Zanotelli et al., 2025). In general, the literature reports the use of statistical distributions for degradation and time-to-failure analysis, stochastic models to represent event occurrence and state dependencies, as well as Monte Carlo simulations for uncertainty propagation and assessment of the impact of modeling assumptions (Mandelli et al., 2023). These models are frequently integrated into Probabilistic Risk Assessment (PRA) frameworks, enabling the quantification of the relative importance of systems and components and their contribution to the overall plant risk (Cancemi et al., 2023; Zanotelli et al., 2025).

Traditional reliability analysis tools, such as FMECA, Fault Tree Analysis (FTA), and Event Tree Analysis (ETA), continue to play a relevant role in supporting the identification of dominant failure modes, the logical modeling of system failures, and the representation of initiating-event progression scenarios, particularly within the context of PRA and risk-informed inspection and maintenance (Mandelli et al., 2023). In parallel, there is a growing body of work on hybrid approaches that incorporate fuzzy logic and Bayesian networks, aiming to address epistemic uncertainties and integrate expert knowledge into nuclear safety analyses, although their practical application often remains at exploratory or methodological stages (Zanotelli et al., 2025).

Advanced computational tools have increasingly assumed an important role in supporting decision-making related to inspection and maintenance. Stochastic simulation models are employed to evaluate inspection and maintenance policies under different risk levels and operational constraints, contributing to cost-benefit analyses and resource prioritization (Werbinska-Wojciechowska et al., 2025). The concept of digital twins has been explored as a virtual representation of systems and components, integrating operational data and degradation models with the objective of supporting condition monitoring and early detection of anomalous behavior throughout the component life cycle (Cancemi et al., 2023; Khosrowpour & Jamshidi, 2026). In addition, machine learning techniques (including artificial neural networks and supervised and unsupervised learning methods) have been investigated for failure prognostics, anomaly detection, and enhanced interpretability of predictive models in complex nuclear systems (Cancemi et al., 2023; Zanotelli et al., 2025).

The principles of Risk-Based Inspection (RBI) are adapted to the nuclear sector through Risk-Informed In-Service Inspection (RI-ISI) methodologies, in which nuclear safety significance is prioritized over purely economic criteria (Mandelli et al., 2023). The literature primarily focuses on applications involving primary circuit piping, reactor pressure vessels, steam generators, and safety injection systems, which are critical components in PWR-type reactors (Cancemi et al., 2023). Case studies report reductions in inspection scope and costs while maintaining or even increasing operational safety margins, although such outcomes depend strongly on modeling assumptions and applicable regulatory requirements (Zanotelli et al., 2025).

Despite these advances, relevant limitations persist, including conservative assumptions imposed by regulatory frameworks, limited availability of high-quality operational data, and still partial integration of PRA results into optimization and decision-support algorithms. These factors constrain the full adoption of dynamic and adaptive RBI strategies in the nuclear sector, particularly those based on continuous updating of reliability and risk parameters (Mandelli et al., 2023; Werbinska-Wojciechowska et al., 2025).

3.2.1. *Research areas identified*

a) Simulation- and machine learning–based optimization: Studies within this research area emphasize cost reduction, increased availability, and improved decision support. Observed trends include stronger integration with condition monitoring data, progressive updating of reliability parameters, and coupling with digital twins and machine learning-based predictive models, particularly for prognostics and anomaly detection (Khosrowpour & Jamshidi, 2026; Cancemi et al., 2023).

b) Application of RBI/RI-ISI in inspection and maintenance: This research area focuses on methodological comparisons, risk categorization and prioritization criteria, and the definition of inspection frequencies based on PRA. Efforts toward international harmonization and standardization are observed, although significant variability remains among regulatory practices and levels of integration between risk analysis, inspection planning, and operational decision-making (Mandelli et al., 2023; Zanotelli et al., 2025).

4. Discussion of the results

The results demonstrate a consistent evolution toward quantitative, data-driven, and computationally intensive approaches for managing reliability and safety in nuclear power plants.

Despite the observed methodological advances, the direct and comprehensive application of Probabilistic Risk Assessment (PRA) to the full optimization of inspection plans remains limited. Challenges persist regarding the integration of advanced computational tools with regulatory acceptance requirements.

Nevertheless, the literature highlights significant opportunities for the incorporation of artificial intelligence, predictive maintenance techniques, process digitalization, and advanced optimization algorithms, such as the Cuckoo Optimization Algorithm (COA), indicating substantial potential for enhancing nuclear inspection strategies.

5. Conclusions

The conduct of this SLR enabled the mapping of research trends and the identification of gaps, such as the still limited application of PRA and RBI to the comprehensive optimization of inspection plans for PWR plants, thereby providing a structured foundation for the development of future research and more robust practices in the field of nuclear safety. The analyzed literature indicates that, although RBI and RI-ISI approaches are well established, their full integration with PRA and advanced computational optimization techniques remains an open research frontier with high potential impact for the nuclear industry.

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